

# Combining Panchromatic and Multispectral Imagery from Dual Resolution Satellite Instruments

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A procedure is developed for combining high spatial resolution panchromatic data with lower resolution multispectral data in order to produce high spatial resolution digital data in multispectral form. Data simulating the French SPOT satellite were processed to resemble high altitude aerial photography, but image artifacts can hamper photointerpretative methods.

## Introduction

Since the launch of Landsat 4 in 1982 the scientific community has been provided with high quality digital images of the earth's surface. In the mid and late 1980s data of 10 m spatial resolution will be acquired from the Satellite Pour l'Observation de la Terre (SPOT), and future Landsat satellites will add a 15 m panchromatic band to the current 30 m Thematic Mapper channels. Such data provide opportunities for detailed observation of processes at the earth's surface, and for mapping of urban areas and description of land use. As pointed out in a recent paper by Cliche et al. (1985), the SPOT data may be processed by image enhancement algorithms to yield visual products resembling color aerial photography.

Although many applications of such data will involve mapping of urban and suburban areas, there are possible uses requiring both high spatial resolution and large area coverage. For example, each 5 years the Soil Conservation Service of the U. S. Department of Agriculture carries out an inventory of the condition of non-federal rural lands in the United States

(USDA, 1982). At present photointerpretation of aerial photography is being considered for assessing land use and land condition. Application of automated techniques to digital satellite data may be an effective tool at some future time, depending on the quality and cost of satellite data, and the availability of procedures for extracting the desired assessment of large areas.

In this paper a technique is developed for combining dual resolution digital data, as from SPOT and the planned Thematic Mappers, to produce high spatial resolution multispectral data. The goal of this work is essentially equivalent to that of Cliche et al. (1985), except that the analysis is based on statistical properties in the data, rather than an ad hoc approach which seeks an optimum image display. In particular, the analytic approach may serve as a basis for design of future earth observing systems, and the resultant products, representing a reconstruction of high spatial resolution multispectral data from a sampled data set, are suitable for further numerical studies, such as computer classification. The basis for the technique depends on the substantial redundancy existing in most high resolution

multispectral satellite data. This redundancy implies that properly chosen data subsets, as from SPOT, may be processed to yield data simulating that from a less sophisticated but more powerful (and expensive) observing instrument.

Despite the attractiveness of this approach some sacrifices are expected when the data acquired by a remote instrument represent a sample rather than a complete coverage high resolution multispectral data set. Variability associated with a number of unknown causes cannot be fully removed, so that resultant data products have a residual noise component. The construction of high spatial resolution data sets from combined panchromatic and multispectral data is discussed in the next section. In the third section the limitations of the planned technology for image analysis are illustrated through an example drawn from Thematic Mapper data. In some cases image artifacts may be present which are distracting at best and which may confuse photointerpretation.

### Estimation of 10-m Multispectral Data

In several recent papers (Price, 1984a,b) the substantial redundancy of Landsat and SPOT simulation data has been illustrated by computation of the information content of actual data, as compared with the information which could, in principle, be acquired by the remote sensor. It appears that in a typical agricultural scene the information content represents about 40% of the data length of standard format digital data. Thus, in principle, such data could be encoded and compressed by approximately 60% without reducing the utility of the data.

In this paper "information" is used in the original sense of Shannon (1948), i.e., as a statistical representation of the variability in a data set. As has been pointed out (Ter Harr, 1961; Price, 1984b), the term "entropy" is often used in the engineering literature as a synonym for the word "information," despite the possibility of confusion with the thermodynamic definition of entropy. In this paper information refers to the variability of a set of observations having a probability distribution  $p_i$ ,

$$H = - \sum_{i=0}^{DN_{\max}} p_i \log_2 p_i,$$

where the  $p_i$  represent the probability of a given measurement value, often called digital number or  $DN$ . For example, a series of observations corresponding to random numbers in the range of 0–255, with each value having a probability of  $1/256$ , has an information value of

$$H = - \sum_{i=0}^{255} (1/256) \log_2 (1/256) = 8 \text{ bits.}$$

As discussed by Price (1984a), Thematic Mapper data from agricultural areas generally are rather restricted in range, and tend to group about a mean value, yielding an information content of 4–5 bits per pixel per spectral channel instead of the theoretically possible 8 bits. Correlation among spectral channels further reduces the information content of multispectral data. The choice of spectral channels for the SPOT instrument results in a very high correlation among channel 1 (0.50–0.59  $\mu\text{m}$ ), channel 2 (0.61–0.68  $\mu\text{m}$ ), and channel 4, the panchromatic channel (0.51–0.73  $\mu\text{m}$ ). Thus the count

values from each pixel in one of these channels may be used to predict the count value of this pixel in the others, to within a small probable error. A joint probability function may be computed from which it is possible to estimate the reduction of information content associated with the redundant spectral channels (Malila, 1985). It is this redundancy which permits the estimation or reconstruction of high spatial resolution multispectral data.

Because the scale of 10 and 20 m resolution data is much smaller than the typical scale of spatial variability for most land areas there is a pronounced tendency for spatial redundancy in the image data, i.e., each pixel tends to be similar to the surrounding ones. This suggests the use of a suitable transformation, e.g., a delta or difference transformation, in which each pixel value except the first is replaced by its difference with its neighbor in the data stream. This has the effect of replacing larger numbers representing the satellite observed radiances, with the differences, which are generally much

smaller. In fact, the 10 m SPOT data can be encoded in the spacecraft in an 8-5-5-8 format for four successive pixels, with the 5-bit data words representing the difference between the actual count value and the interpolated value derived from the end-point 8-bit words. Obviously, the 5-bit words cannot, in general, retain the full accuracy of the 8-bit values, but a lookup table with expanded ranges for the large (and improbable) difference values is used to retain the major part of the information of the full 8-bit data.

As illustrated in Fig. 1, the dual resolution image data from SPOT and the future Thematic Mappers combines the spectral redundancy due to the overlap of the spectral intervals in the visible, with the spatial redundancy of the panchromatic channel, as four 10-m pixels lie within a single multispectral pixel. Because the 10-m data are very highly correlated with channels 1 and 2, but much less correlated with channel 3, the two cases will be discussed separately. The

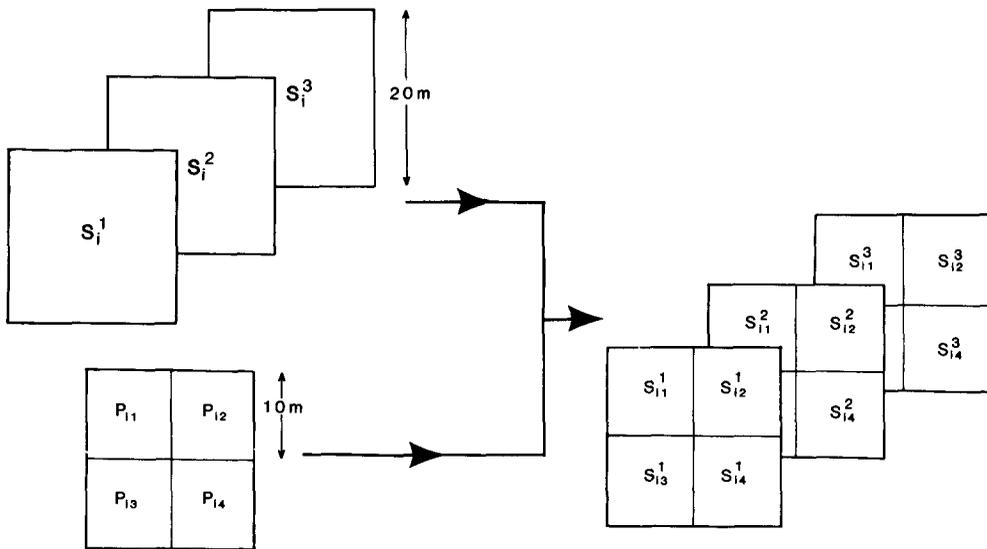


FIGURE 1. The considerable spatial and spectral redundancy of the 10 and 20 m data permits the construction of high resolution multispectral data.

methodology to be developed resembles the procedure used in the treatment of the SPOT simulation data (SPOT Image Corp., 1983).

### Combination of channels 1 and 2, and panchromatic data

From statistical analysis of the SPOT data one finds that data from channels 1 and 2, and the panchromatic channel, to be numbered 4, are all highly correlated. Thus

$$X_i^m = a_{mn} X_i^n + b_{mn}, \quad m \neq n = 1, 2, 4$$

where the superscript represents the channel number, the subscript  $i$  the pixel number, i.e., on an image line, and  $a_{mn}$  and  $b_{mn}$  are determined by a best-fit procedure to a sample of the data. This relationship is sufficient to estimate the 10-m multispectral values from the channel 4 data with a high degree of accuracy. The residual error may be reduced by using the known value of the 20-m pixels for channels 1 and 2, as follows: Let the smaller (10 m) pixels be identified by  $x_{ij}$ ,  $j = 1-4$ . Then using the channel 4 values to estimate 1 and 2,

$$x_{ij}^m = a_{m4} x_{ij}^4 + b_{m4} + \delta_{ij}^m, \quad m = 1, 2$$

where  $\delta_{ij}^m$  is the error in the estimated value  $x_{ij}^m$ . However, the average of the four subpixel values must equal the measured value  $X_i^m$  of the 20-m pixel. Thus one may compute a correction factor  $f = X_i^m / [0.25 \sum_{j=1}^4 x_{ij}^m]$  such that the correct sum is obtained for the four 10-m pixels, i.e.,

$$x_{ij}^m = X_i^m (a_{m4} x_{ij}^4 + b_{m4}) / \left[ 0.25 \sum_{j=1}^4 (a_{m4} x_{ij}^4 + b_{m4}) \right].$$

If  $b_{m4}$  is zero, then this result is the same as that used in the SPOT simulation program (SPOT Image Corp., 1983, p. 25), i.e.,

$$x_{ij}^m = X_i^m x_{ij}^4 / \left[ 0.25 \sum_{j=1}^4 x_{ij}^4 \right].$$

However,  $b$  is generally nonzero.

The validity of this procedure was tested using SPOT simulation data from Washington, DC. Since 10-m four-channel data were not available, the verification was carried out by averaging the three channels of 20-m data and the single channel 10-m data to 40 and 20 m, respectively. Application of the above procedure to the averaged data produced 20 m values for channels 1 and 2, which were compared with the original true values at 20-m resolution. Residual errors were of the order of 2 counts as compared to the standard deviation of about 20 counts in the original data, i.e., the 20-m channel 4 data described 99% of the variance of 40-m data in channels 1 and 2. This suggests that the panchromatic data can provide an excellent estimate of the 10 m values in channels 1 and 2.

### Combination of Channel 3 and panchromatic data

The procedure described in the previous subsection is unsatisfactory for the channel 3 data because the visible and near infrared spectral channels are not linearly related. In the SPOT Simulation Program cubic convolution interpolation was used to create 10-m pixels from the 20-m data. This method discards entirely the information provided by the panchromatic channel of data. In addition, it does not satisfy the integral property that the four 10-m pixels must average to the 20-m

value. A scaled one-dimensional example is appropriate; if a measurement  $S_i$  is obtained at  $x = 0$ , representing the interval  $(-1/2, 1/2)$ , then interpolated values  $S_{i1}$  at  $-1/4$ , representing the interval  $(-1/2, 0)$  and  $S_{i2}$ , at  $+1/4$ , representing the interval  $(0, +1/2)$ , must average to the original value  $S_i$ . However, from cubic convolution the values are given by  $S_{i1} = 0.070S_{i-2} + 0.227S_{i-1} + 0.867S_i - 0.023S_{i+1}$  and  $S_{i2} = -0.023S_{i-1} + 0.867S_i + 0.227S_{i+1} - 0.070S_{i+2}$ , with the average equal to  $-0.035(S_{i-2} + S_{i+2}) + 0.102(S_{i-1} + S_{i+1}) + 0.867S_i$ . We note in passing that "cubic convolution" is no longer uniquely defined, as the coefficients used for interpolation of Landsat MSS data were modified at some point in time during application to Thematic Mapper data (Fischel, 1984) These weighting coefficients are given by

$$\begin{aligned} w_1 &= ad(1-d)^2, \\ w_2 &= (a+2)d^3 - (a+3)d^2 + 1, \\ w_3 &= -(a+2)d^3 + (2a+3)d^2 - ad, \\ w_4 &= ad^2(1-d), \end{aligned}$$

with  $a = -1$  for MSS data and older Thematic Mapper data, and  $a = -1/2$  for newer Thematic Mapper data. Here  $d$  is the distance  $(0, 1)$  from point  $x_2$  and  $x_3$  in the series of four points,  $x_1, x_2, x_3, x_4$ .

A more general relationship than the linear fit of the previous subsection between the 10-m data and coregistered 20-m data is obtained by computing the expected (mean) value for channel 3 for each given value in channel 4, after the 10-m data have been averaged to 20 m. Thus

$$x_{ij}^3(x_4) = \bar{x}^3(x_4),$$

where  $\bar{x}^3(x_4)$  is the mean value of  $x_3$  for all picture elements in the image which have the given value  $x_4$ . These 256 values for  $x^3(I)$  for  $I = 0-255$  are obtained while the  $a_{mn}$  and  $b_{mn}$  values are being derived for channels 1 and 2. Derivation of 10-m data for channel 3 is thus a simple lookup of the predicted value, given from the known value of  $x_4$ . The resulting four nested pixels are then corrected as in  $B$  for the fact that the initial estimate of the sum does not generally agree with the measured value.

This technique was applied to averaged 10- and 20-m data as described in the previous subsection. This procedure is only moderately successful, with the predicted values for channel 3 accounting for about 75% of the variance of the original data. Several alternative algorithms were tested, with nearly identical conclusions; i.e., there does not seem to exist a general procedure which can derive highly accurate values for 10-m pixels of channel 3. The reason is readily established from inspection of the two-dimensional histogram of channel 3 data vs. channel 4 data, as illustrated in Fig. 2.

Evidently low values of reflectivity in channel 4 may be associated either with low values of reflectivity in channel 3, as from shadows or water, or with high values of reflectivity in channel 3 due to vegetation. Low correlation between spectral channels is favorable for spectral differentiation and classification, but unfavorable for inference of high spatial resolution multispectral values from dual spatial resolution data. The channel 3 ambiguity is especially severe in the Washington, DC scene which was used for this study, as many city pixels contain both shadows of buildings and trees. The problem is expected to be less severe for agricultural scenes, but the accuracy of

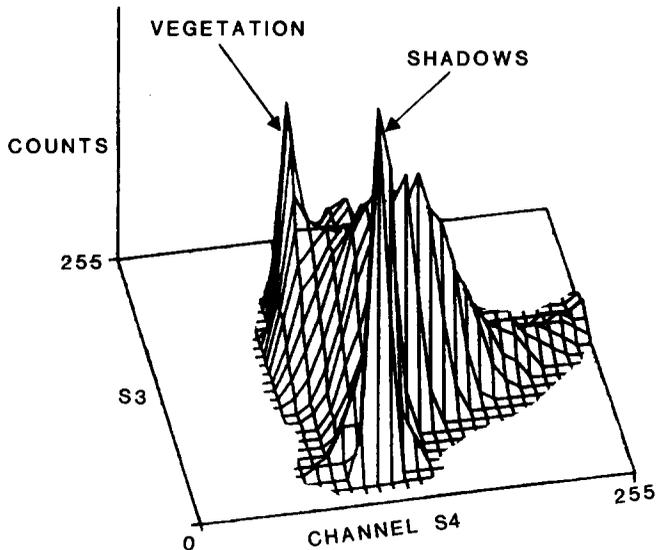


FIGURE 2. Two-dimensional histogram of SPOT channels 4 and 3, illustrating that a value in channel 4 does not specify adequately the value in channel 3, especially for low values in channel 4.

the procedure depends on the nature of the scene, in general.

Although derivation of the fitting parameters for the spatial interpolation appears to require an additional step of computation, such statistical properties may be readily obtained during calibration and production processing of the satellite data before distribution to data users (e.g., NASA, 1978).

### Artifacts and Spatial Interpolation

With the advent of higher spatial resolution digital data it is possible to resolve not only evidence of man's influence on the earth's surface, such as agricultural fields, dams, street and road patterns, etc., but also considerable spatial detail in these features. Figure 3 illustrates combined panchromatic and multispectral imagery of the nation's capitol in the District of Columbia, as derived from the methodology described in the previous

section. Considerable detail is evident, suggesting that the increased spatial resolution (10 m) of SPOT data will be of great value for studies of urban land use and for photointerpretation generally. Figure 4 shows that even very small features may be inferred from the 10-m data under optimum conditions.

Unfortunately, even the high spatial resolution data are susceptible to sampling limitations due to within pixel averaging. This averaging can produce peculiar effects when evaluated by photointerpretation. From canals on Mars to linears as mapped by geologists, line segments produce a strong response from the human visual system. Caution must be exercised when high contrast linear features are present in image data. The following example and its quantitative explanation illustrate the potential problems associated with narrow linear features as well as a possible solution for image restoration. However, there appears to be



FIGURE 3. Washington, DC: the Capitol building is at the center of the 2.5 km square area.

no general procedure for eliminating artifacts except oversampling, i.e., imaging each point more than once. Of course, oversampling provides very little additional information about the land surface, serving mostly to smooth out the image defects which occasionally result from the 1-1 sampling of instruments such as SPOT and the Landsat Thematic Mappers.

Figure 5 illustrates the appearance of dark, narrow strips, i.e., parallel roads separated by several hundred meters, as

recorded by the Landsat 4 Thematic Mapper on 12 December 1982 (Scene ID 40149-17444). The peculiar ladderlike appearance results from the scale of the display, where magnification permits discrimination of individual detector responses as they cross over the road surfaces. Figure 6 illustrates an idealized nadir view of a narrow dark linear feature in Fig. 6(a), the averaging effect of the large pixel size and the resultant detector responses for three adjacent detectors in Fig. 6(b), and an analytic solution in Fig.

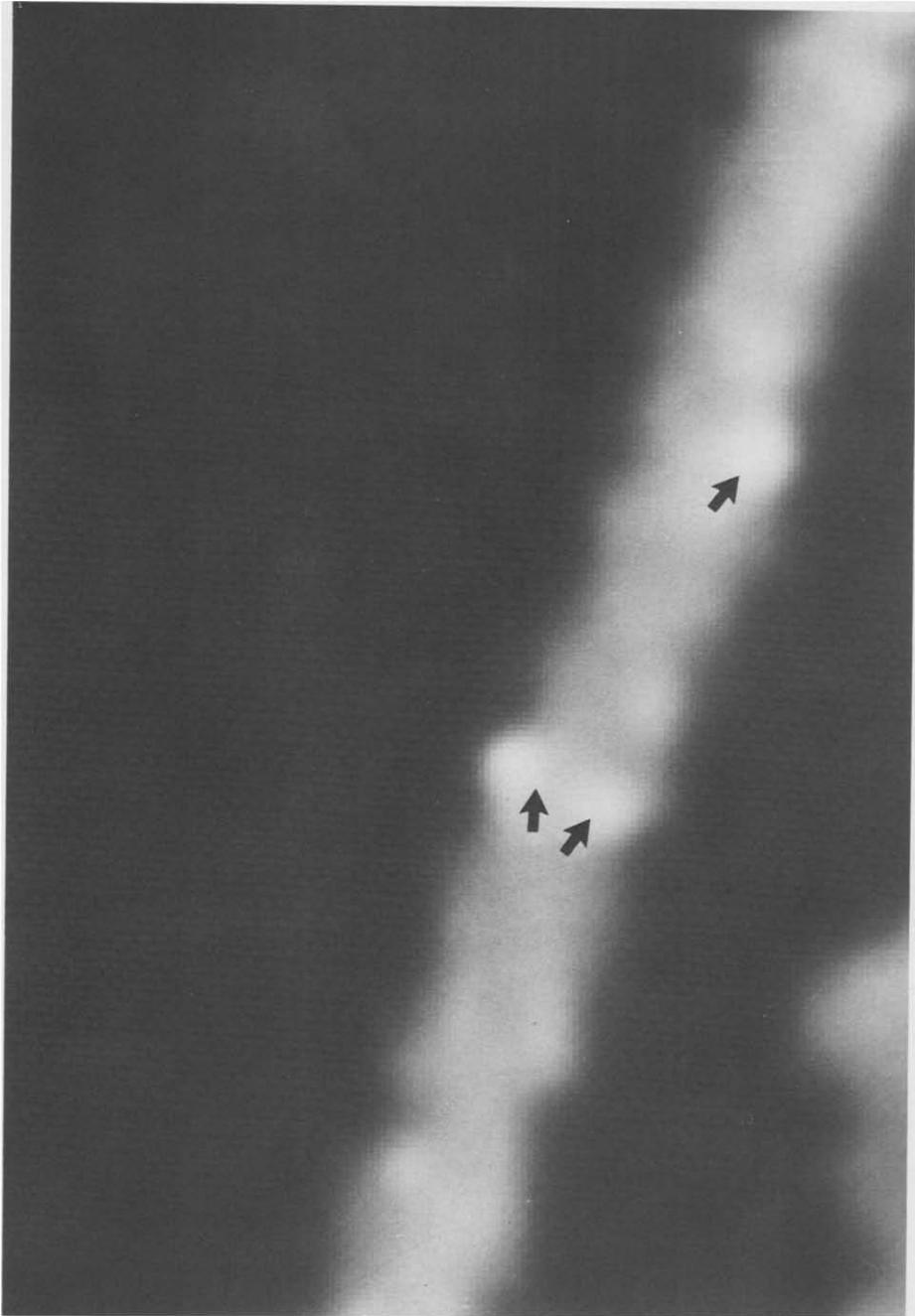


FIGURE 4. Under optimum conditions features as small as automobiles may be recognized in the SPOT 10 m data. Cars are not resolved in the matching aerial photography, but their placement with respect to lane markers is sufficient for positive identification.

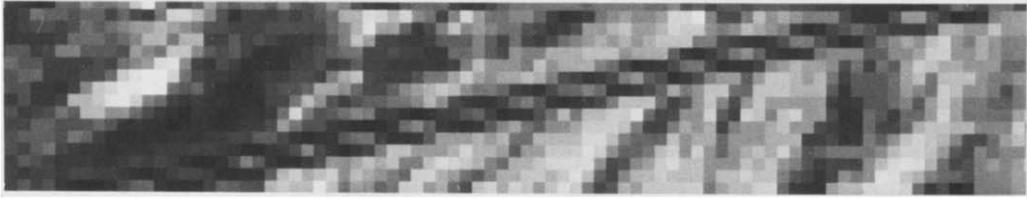


FIGURE 5. Thematic Mapper image of a divided highway 15 km west of Blythe, CA. The striping represents responses of individual detectors.

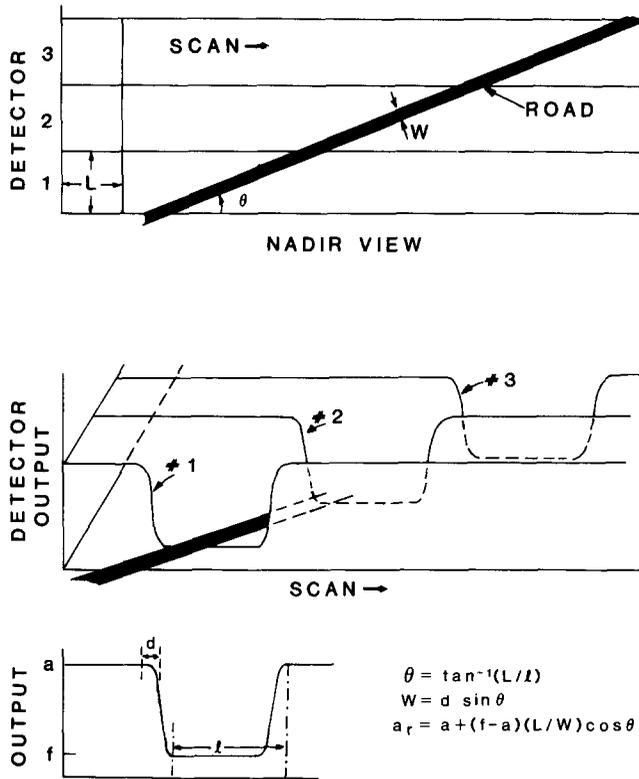


FIGURE 6. Schematic representation of a single narrow line (road) as viewed from above (a), the corresponding outputs for adjacent detectors (b), and the solution for the relative detector/road angle, the width of the road, and the reflectivity of the road, given idealized measurements (c). Note that the result is not produced by scan direction; i.e., the same image would be produced by scan motion in the perpendicular direction.

6(c), assuming a background reflectivity  $a$ , and a road reflectivity given by  $a_r$ . Although solution for  $\theta$ ,  $w$ , and  $a_r$  is possible in this idealized case, given the continuous trace from only the one detector, in practice the uncertainty in estimating the rounding width ( $d$ ), the change in detector output as compared to back-

ground, etc., strongly suggest using averages from a number of appropriately shifted image lines. If the configuration is recognizable by an image analyst, then magnification and interpolation may be used to restore the linear features to their accustomed appearance. While an image analyst may readily identify this

particular type of image artifact, the situation in geometrically complex urban areas, given differing sizes and shapes of buildings and roads, etc., is not favorable. Simple interpolation of the image does not improve the display of features such as that in figure 5.

### Conclusion and Outlook

In this paper the techniques for producing equivalent high resolution multispectral data have been discussed in the context of the information content of the image data. To the extent that such methods are feasible there exist a number of promising developments:

1. The design of better sensors, with the choice of spectral intervals, spatial resolution, and precision selected on the basis of the information content of the data vs. the cost of instrumentation and data handling.
2. The use of coding techniques, both in the spacecraft and in ground processing, to reduce data volumes and simplify the task of image analysis and interpretation.
3. The development of specialized interpolation and display techniques to bring out the maximum detail in digital data, using human guidance if necessary. The photo enhancement techniques of Cliche et al. (1985) are in this domain.

Clearly, the new generation of satellite sensors open new opportunities for applications to the earth sciences.

A Fortran listing for interpolating linear features, e.g., roads, may be obtained from the author.

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